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WHEEL DEFECT STATISTICAL ANALYSIS: CANADIAN COAL TRAINS

prepared for the

Transportation Development Centre

by

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17. Abstract

This report presents the results of a statistical study undertaken to determine those defects which contribute most to system wheel cost and also attempts to isolate the factors which contribute to such failures. The data used was obtained from the maintenance records of 100-ton gondola cars. A number of factors were considered for grouping purposes, including route travelled, type of side bearings, type of car and steerable versus non-steerable trucks. It was found that significant differences occurred in the relative incidence of particular failure types for the car groupings utilized. Also, it was shown that various factors can have significant effects on the mean mileage between wheel failures. Finally, the potential benefits of a Wheel Failure Reporting System are reviewed.

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17. Résumé

Ce rapport donne le résultat d'une étude statistique visant à déterminer les défauts qui contribuent le plus à faire élever les dépenses du poste organes de roulement, en plus d'identifier les facteurs à l'origine de ces défauts. Les données de l'étude ont été tirées des archives d'entretien concernant les wagons tombereaux de 100 tonnes. Le groupement de ces données a été fait d'après plusieurs paramètres: tracé de la voie, type de glissière, bogie orientable ou non. L'étude a mis en évidence des différences statistiques intéressantes dans la fréquence relative d'un type de défaut, selon le groupe considéré. De plus, il a été constaté que ces divers facteurs ont une influence directe sur la distance moyenne de bon fonctionnement. Enfin, le rapport passe en revue les avantages possibles d'un système de compte rendu sur ces différents types de défauts.

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SUMMARY

A statistical analysis of representative wheelset repair data from Procor, CN Rail and CP Rail has been performed to determine significant influencing factors on freight car wheel life.

Wheel repair is a major cost component of railway operations. Besides material costs and maintenance labour, there are opportunity costs associated with cars out of service. Fleet size, maintenance shop size and staffing, and other operation decisions are then influenced. This pilot study was commissioned by the Freight Car Working Group of the Railway Advisory Board. With funding provided by the Transportation Development Centre, CIGGT engaged Dr. T. Moore of Queen's University to perform the study.

Data was provided on a confidential basis for the coal car fleets of Procor, CN Rail and CP Rail. The volume of data was significant enough for a valid statistical analysis of mechanical (car-based) and geographical influences on wheel life. Metallurgical variables (base material, defect growth, thermal stresses, etc.) are not available for inclusion in the analysis. The data was processed with SYSTAT on a PC microcomputer.

The analysis confirmed some common knowledge about wheel life and raised some questions about unexpcted correlations. Some factors had no influence on particular defects.

- There is a large variation (standard deviation in wheel life within the groupings based on route, truck type and bearing type.
- Shelling dominates wheel failures throughout. There is insufficient data to determine the influencing factors.
- Steerable trucks influence several failure modes, most notably thin flange.
- Rolling element side bearings are less damaging to the wheels than resilient element side bearings.

A wheel failure reporting system which provides engineering and maintenance personnel with the ability to monitor the influence of certain operating or mechanical variables on wheel life would be beneficial for developing methods to reduce wheel costs.

It is recommended that other fleet records be brought into the analysis. More detail in the reporting of wheel maintenance is also expected to refine the analysis.

SOMMAIRE

Une étude statistique a été faite à partir des archives fournies par Procor, CN Rail et CP Rail sur l'entretien des essieux montés, afin de déterminer les facteurs dont l'influence est la plus grande sur la durée de vie des organes de roulement.

L'entretien des organes de roulement figure parmi les coûts les plus élevés de toute exploitation ferroviaire car, en plus du coût des matériaux et de la main-d'oeuvre, il faut tenir compte du manque à gagner résultant de la non disponibilité des wagons. Ces facteurs se répercutent à leur tour sur d'autres aspects de l'exploitation, comme la taille du parc, le dimensionnement des ateliers d'entretien et le nombre de personnes à affecter à ces travaux. Cette étude pilote a été faite à la demande du groupe de travail Wagons de marchandises, faisant partie du comité consultatif ferroviaire et avec le concours financier du Centre de développement des transports. Le contractant, le CIGGT, a retenu les services du Dr. T. Moore de la Queen's University en Ontario.

Les données de base, fournies à titre confidentiel par Procor, CN Rail et CP Rail, ont été suffisamment abondantes pour justifier une étude statistique valide des défauts de nature tant mécanique que géographique susceptibles d'affecter les organes de roulement. Les variables de nature métallurgique (matériau de base, crossance des défauts, contraintes thermiques, etc.) n'ont pas pu être prises en compte. Les données ont été traitées sur un SYSTAT piloté par un micro-ordinateur.

L'étude a confirmé ce qu'on savait déjà sur les facteurs influençant la durée de vie des roues, mais a mis en évidence certaines corrélations inattendues; par contre, d'autres facteurs sont totalement étrangers à la question.

- Des écarts statistiques intéressants (écarts types) ont été mis en évidence, selon le groupe de classement considéré: itinéraire, bogie, glissoir.
- Le défaut d'écaillage prédomine, mais il n'a pas été possible d'en déterminer les facteurs contributifs essentiels.
- Les bogies orientables influent sur certains types de défauts, notamment l'amincissement du boudin.
- Les glissoirs à éléments roulants sont moins dommangeables aux roues que ceux à éléments souples.

Un système d'archivage des défauts de roues qui apporterait des renseignements très utiles concernant l'influence de certaines variables sur la durée de vie des roues sera profitable à developper des méthodes pour reduire le coût des roues.

Le rapport recommande que les archives d'autres entreprises soient fournies aux fins d'analyse et que les comptes rendus d'entretien soient plus détaillés de manière à permettre une étude statistique plus détaillée.

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1. OBJECTIVE

This is a preliminary study undertaken to determine the practicality and potential benefits of a large-scale study of available railway freight car wheel defect data. It was desired to identify those defects which most contribute to system wheel cost and also attempt to isolate the factors which contribute to such failures.

It is expected that such information, coupled with further study, will ultimately provide a means of predicting wheel life for a given set of operating conditions. Further, if such relationships could be identified, it would then be possible to identify projects of highest potential benefit for development of better operating procedures or equipment.

2. INTRODUCTION

By far, the most frequent type of repair to freight cars is changeout of wheelsets. Also, it has been noted that the wheel life between changecuts varies widely, from less than 50,000 miles to more than 400,000 miles. Such variations have become particularly noticeable since the advent of unit trains. In this instance there are large numbers of nominally identical wheels on these trains, all undergoing apparently identical service, yet significant variations in wheel life still persist. No particular factors have yet been identified which could account for such extremes.

Naturally, an understanding of the factors affecting wheel life would bestow significant economic benefits upon the railways. A means for maximizing wheel life and also minimizing maintenance costs associated with wheel changeouts is needed.

There is no question but that the ability to improve wheel service life is dependent upon a basic understanding of the wheel experience and the capability to predict the effect of service variables on wheel life expectancy. This is a particularly challenging task, since the external influences on wheels are multi-dimensional, relating to a large number of interdependent parameters.

Wear parameters can be classified into broad categories in order to facilitate their study and correlate these functions in an applicable

wheel wear predictor. A common approach is to divide these parameters into three domains: metallurgical, rheological, and mechanical.

It is beyond the scope of the present study to investigate each of these areas individually, and in depth. As such, attention will be focussed on the mechanical parameters since these are, to varying degrees, quantifiable from "in service" and maintenance records. This approach considers the metallurgical and rheological parameters to be "constants" for the wheel sets investigated. Obviously such is not the ideal approach; however, a far more ambitious study (both in time and money) would have to be undertaken to remove these deficiencies.

Within the mechanical domain, the types of factors to be considered in this study include: type of track (defined by route), type of side bearings, type of car, and steerable versus non-steerable trucks.

3. LITERATURE SURVEY

As a first step in this study, a literature review was undertaken to determine if results of statistical studies similar to the one envisaged in the present study have been published in the open literature. It soon became aparent that no such studies existed in the literature, with published studies on wear and failure of wheels concentrating generally on a microscopic understanding of these phenomena or considering the effects of vehicle dynamics on the wheel failure problem.

These papers will not be reviewed here since they do not relate directly to the present study. However, a bibliography has been included which lists these papers for reference purposes.

4. METHODOLOGY

Since the present study is preliminary in nature, with limited scope, the data reviewed was restricted to that available from coal trains employing 100-ton gondola cars.

The data used was supplied by Canadian National Railways, Canadian Pacific Railway, and Procor Limited. Table 1 provides a summary of the car numbers for which varying degrees of information were made available.

TABLE 1

LIST OF CARS

Canadian National		Canadian Pacific		Procor	
Car Number	Year Built	Car Number	Year Built	Car Number	Year Built
CN199000-CN199199	1970	CP349364-CP349819	1970	CN199294-CN199567	1975 (HS)
CN199200-CN199293	1974	CP351300-CP351699	1971		
CN199294-CN199567*	1975	CP351700-CP352200	1976		
CN199600-CN199899	1981	CP352200-CP352443	1980		
CN/CNHX197500-CN/CNHX197599	1978	CP352444-CP352853	1982		
		CPHX799532-CPHX799999	1978		

* Procor lease

Once the data were obtained, they were reviewed to determine the precise information provided by each company and the time period spanned by the records. This was necessary to permit definition of those factors which might be related to wheel failure and which were available for several definable groupings of cars, thus permitting comparisons to be made between groups. In this instance "definable group" refers to cars which are nominally identical except for a particular well-defined characteristic. As an example, two "definable groups" might consist of cars which are nominally identical except that one group has been converted to steerable trucks, while the other has not. Or, perhaps, nominally identical cars run on two very different routes, such as "prairie" and "mountain." In a number of instances possible factors of interest had to be abandoned since no comparison group could be found in the available data base.

Once the data had been reviewed and available failure-related variables had been identified, the repair records and associated mileage information for each definable group of cars were generated for use with the statistics package. An excerpt from a typical data file is shown in Table 2.

4.1 Statistics Package -- SYSTAT

To perform the necessary sorting and statistical routines required in this study, it was necessary to decide on the statistics package to be used. Due to the volume of data available, it was obvious that a computer-based package was necessary, either mainframe or a smaller system.

The obvious advantages of high processing speed, large data file capacity, and excellent quality output graphics made mainframe packages such as SAS and Minitab initial favourites for use in this study. However, it was recognized that although the processing speed of such packages is high, the actual "turnaround time" can often be quite long. Also, although the data base to be used in this study was large, it was not sufficiently large to necessitate the use of mainframe storage capacity.

The study team decided to use a microcomputer-based statistical package called SYSTAT. This commercially available package provides all the statistical routines that might be necessary and handles data files of the size envisioned for this study. Although the processing speed of given sorting or statistical routines is much lower than that of the mainframe products, the overall turnaround time is actually much better. The available output graphics do not compare with the quality of the mainframe systems; however, it was felt that SYSTAT produced acceptable levels of graphics. More information on the capabilities of SYSTAT can be found in Appendix A.

The results discussed in this section will be presented in two graphic formats: as bar charts and as histograms. It should be noted that the left vertical axis of the histograms will be a "proportion-per-standard-unit" scale. Such a scale represents a probability density scale for distributions having a standard deviation of "1". For a normal distribution, the peak of the distribution would fall at 0.4.

TABLE 2

EXAMPLE OF TYPICAL DATA FILE

	Car No.	Date	Set	Failure	Group
Case 1	22	80-01	3	92	2
Case 2	92	80-01	1	64	2
Case 3	146	80-01	1	64	2
Case 4	147	80-01	1	33	2
Case 5	147	80-01	2	33	2
Case 6	153	80-01	1	93	2
Case 7	220	80-01	2	60	2
Case 8	220	80-01	3	60	2
Case 9	220	80-01	4	60	2
Case 10	223	80-01	2	64	2
Case 11	10	80-02	4	64	2
Case 12	55	80-02	1	64	2
Case 13	55	80-02	2	64	2
Case 14	58	80-02	1	60	2
Case 15	66	80-02	4	60	2
Case 16	81	80-02	1	75	2
Case 17	81	80-02	2	64	2
Case 18	89	80-02	1	75	2
Case 19	94	80-02	2	64	2
Case 20	94	80-02	3	75	2
Case 21	102	80-02	3	64	2
Case 22	110	80-02	3	64	2
Case 23	111	80-02	4	64	2
Case 24	113	80-02	3	64	2
Case 25	117	80-02	3	60	2
Case 26	118	80-02	2	64	2
Case 27	125	80-02	1	64	2
Case 28	126	80-02	2	64	2
Case 29	151	80-02	2	75	2
Case 30	154	80-02	1	78	2

5. DISCUSSION OF RESULTS

Such scaling makes it easier to compare histograms from different sample sizes. It is important to remember that histograms are not bar charts, but sample density estimators.

To maintain corporate confidentiality, the results discussed will not be identified by operator/owner, but simply compared by "definable groupings." That is, the cars will not be identified as CN, CP or Procor cars but as, for example, cars with steerable versus non-steerable trucks (all other variables nominally the same). In this manner various factors of interest to wheel failure may be investigated without identifying the particular freight car operators.

At this point it should also be noted that available repair and mileage records were generally complete back to at least January 1980. If data was provided for a significantly shorter duration, then this fact will be noted at the time the data are discussed.

Since mileage between wheel replacement was an important consideration in this study, great care was taken to properly assess the actual cumulative mileage on a particular wheel set. In a number of instances the cars were operating before the start of the available repair records. In these instances it was not possible to associate a definite mileage to the first wheelset replacement. Even though a cumulative mileage for the car may be known at this first recorded replacement, it is not known whether this was, in fact, the first replacement of that wheelset since the car began service. Due to such uncertainty, the first recorded wheelset replacement for a particular car and axle was not included in the mileage data base, unless the car was known to have entered service after the initiation of the repair record data base supplied by the owner.

5.1 Definable Grouping -- Route

In this section, results for two groups of cars, which have nominally identical construction but which operate on quite different routes, in this instance "mountainous" and "prairie," are reviewed.

5.1.1 Incidence of Failure

Figure 1 shows a summary bar graph which compares the incidence of a particular type of failure (AAR "why made" code; see Appendix B) as a percentage of the total number of wheel-related failures, for both the "mountainous" and "prairie" car groups.

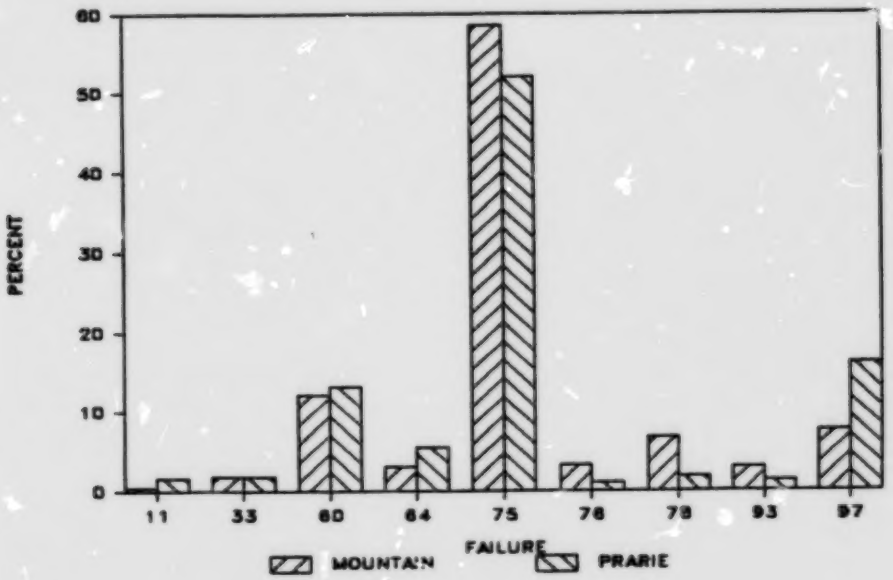

Figure 1 Bar graph of failures for both mountainous and prairie routes

The original data from which Figure 1 was generated are shown in Tables C.1 and C.2 of Appendix C. These tables include all failures noted throughout the period covered by the statistical data base (1980 through 1985). This data is included for completeness, but many of the failure types will not be discussed because their occurrence is relatively rare.

In each case it is apparent that the major cause of wheel replacement is "shelling" (code 75). It is interesting that the incidence of shelling does not seem to vary significantly for the two very different routes represented. This would seem to indicate that braking is not a significant contributor to shelling. This is in keeping with studies by Dewez and Wandrisco (1973) which indicate that shelling is essentially a fatigue failure that is caused by rolling loads. The following should be noted with reference to code 75 in Figure 1:

(a) "prairie" speed is higher, thus leading to a higher impact load which produces more shelling

(b) "mountain" braking is more frequent which leads to higher thermal fatigue and a higher incidence of flats, resulting in more shelling

(A) and (b) even out the final score.

For both routes "loose backing plate" and "thin flange" occupy the second and third rankings, albeit in reverse order. Although the reversal in order is not, in itself, of particular interest, the fact that "loose backing plate" makes up 16 per cent of wheel replacements for the "prairie" route versus only 7.6 per cent for the "mountainous" route would seem to indicate a significant difference in operational or maintenance procedures. What this difference might be is not immediately clear.

The "tread slid flat" failure occupies the fourth ranking for the mountainous route, with almost 7 per cent of wheel replacements occurring for this reason. This is in stark contrast to the 2 per cent rate (7th ranked) for the prairie route. Considering the braking demands made on cars in mountainous regions, this is not unexpected. Also, the incidence of failures due to "built-up tread" (3 per cent of total failures) for the mountainous route is three times that for the prairie route.

It is apparent from this comparison that there are certain differences in the types of failures experienced as a consequence of the "route" parameter, with the difference in braking demands perhaps an important variable. However, by far the most frequent failure is "shelling," approximately 55 per cent of all wheel failures designated for each route. This would seem to indicate that route has little, if any, effect on shelling. Such a large failure rate would also indicate that the ability to reduce shelling would be of significant economic benefit. The development of fatigue resistant steels would seem to be a first priority, since shelling is considered to be a rolling fatigue phenomenon.

5.1.2 Mileage

Additional insight may be gained on the effect of route on wheel failure by looking at failures as a function of mileage rather than by frequency of occurrence, or "incidence," as discussed earlier.

To begin, Figures 2 and 3 show histograms of "total failures" as a function of mileage. In this instance "total failures" refer to the lumping of all reported failures for each group of cars. Such figures thus give an idea of total wheel-related maintenance.

Notice first that, unfortunately, SYSTAT does not plot these and subsequent figures on a common mileage scale. This is a failing of the package which does make comparison somewhat more difficult. Care must be taken in comparing histograms.

For the mountainous route the average mileage on a wheelset at time of changeout due to <u>any failure</u> is 200,000 miles versus 193,000 miles for the prairie route, with the mountainous route having a somewhat greater "spread" of mileage values as evidenced by a higher standard deviation. It is somewhat surprising that the prairie route seems to provide the more hazardous environment with respect to wheel life.

It may be of greater interest to look at individual failure types as a function of mileage.

Recalling the overwhelming incidence of shelling failures shown earlier, Figures 4 and 5 present histograms of incidence versus mileage for shelling (Code 75). The mountainous route shows a greater mean mileage between shelling failure (200,000 miles versus 171,000 miles) than the prairie route. In both cases the significant spread in mileage, as indicated by the standard deviation, is quite striking. However, the differences in mean mileage shown are not significantly different at the 5 per cent level.

It has been suggested (see Wandrisco and Dewez) that although braking stresses do not appear to cause shelling, the formation of structurally weakened metal, as a result of the heat of braking friction, may accelerate the formation of shelling cracks. From this it might be inferred that shelling would occur more frequently (at shorter mileage)

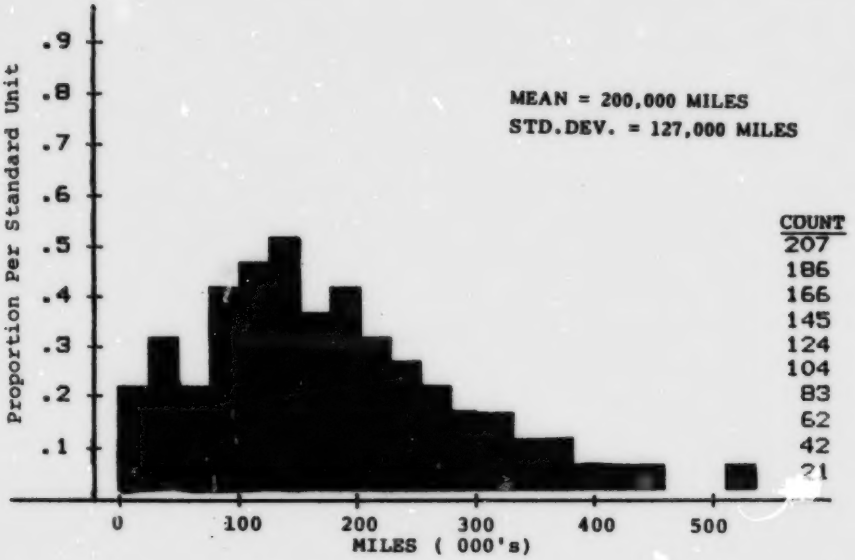

Figure 2 Histogram of all failures as a function of mileage - mountainous route

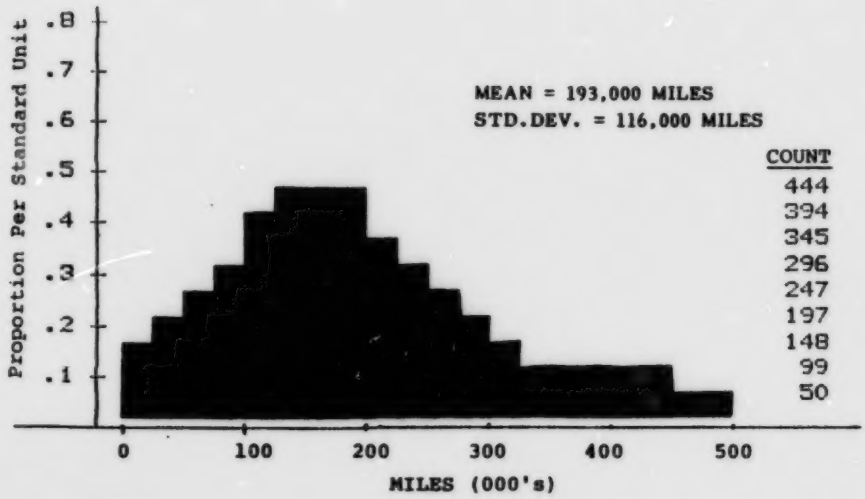

Figure 3 Histogram of all failures as a function of mileage -- prairie route

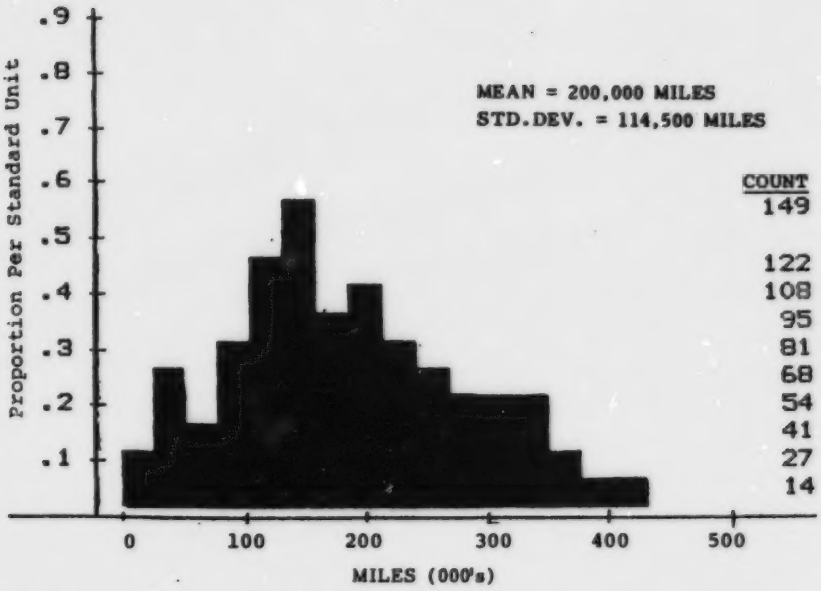

Figure 4 Histogram of shelling failure as a function of mileage - mountainous route

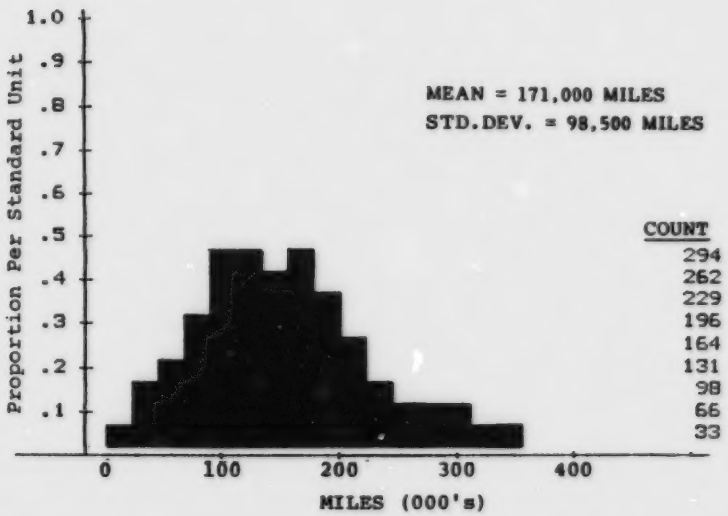

Figure 5 Histogram of shelling failure as a function of mileage -- prairie route

in those circumstances where braking application is most severe, such as mountainous regions (refer to comment on page 7). The data presented in Figures 4 and 5 does not tend to support this line of reasoning.

Figures 6 and 7 show histograms for "thin flange" failures. The mean mileage between failure is essentially identical for both routes, although the variability is slightly greater for the mountainous route.

The data for "high flange" failures is shown in Figures 8 and 9. In this instance the mean mileage between failure is somewhat higher for the prairie route than for the mountainous route. However, it is perhaps more interesting to note that the mean mileage between high flange failure is approximately twice that of thin flange failure, for both routes. It is therefore not surprising that, for both routes, thin flange failures are more prevelant than high flange failures.

5.2 Definable Group -- Steerable Versus Non-Steerable

In this section results for two groups which have nominally identical construction, except for type of truck, are reviewed. The two groups are considered to have run over comparable routes and to have been subjected to similar loading.

5.2.1 Incidence of Failure

Figure 10 shows a summary bar graph of the incidence of failure for cars with non-steerable and steerable trucks. Again, Appendix C contains the original data for all failures noted throughout the period covered by the data base.

Perhaps the most striking features of this data are first, shelling is not the major cause of failure as it was for the cars discussed earlier, and second, the dramatic drop in the percentage of failures due to "thin flange" for the steerable cars.

The reason for the significant drop in shelling failures for both non-steerable and steerable cars compared to the cars discussed earlier is not clear. Certainly a detailed examination of possible differences between these two car groupings may provide clues to reasons for high shelling incidence.

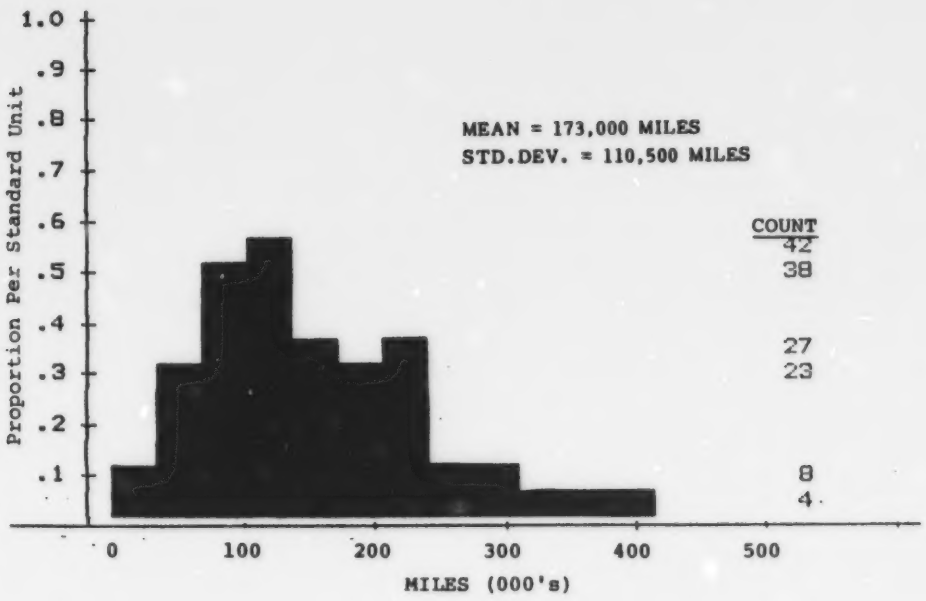

Figure 6 Histogram of thin flange failure as a function of mileage - mountainous route

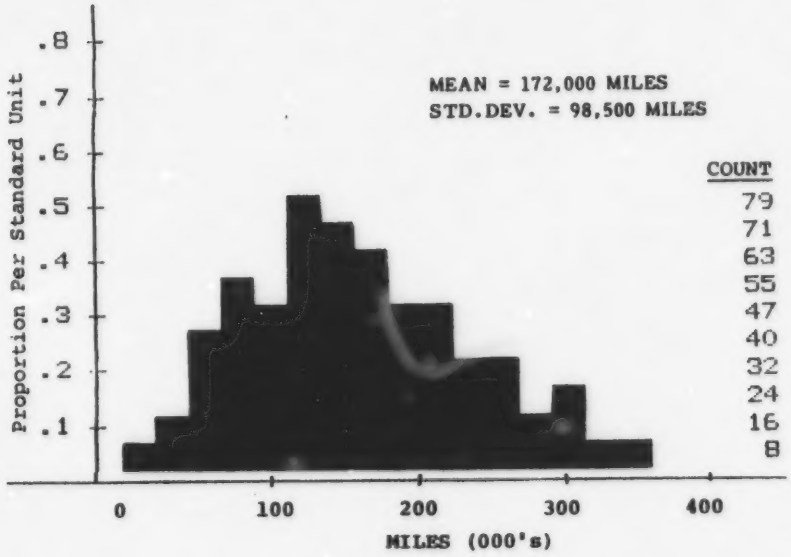

Figure 7 Histogram of thin flange failure as a function of mileage -- prairie route

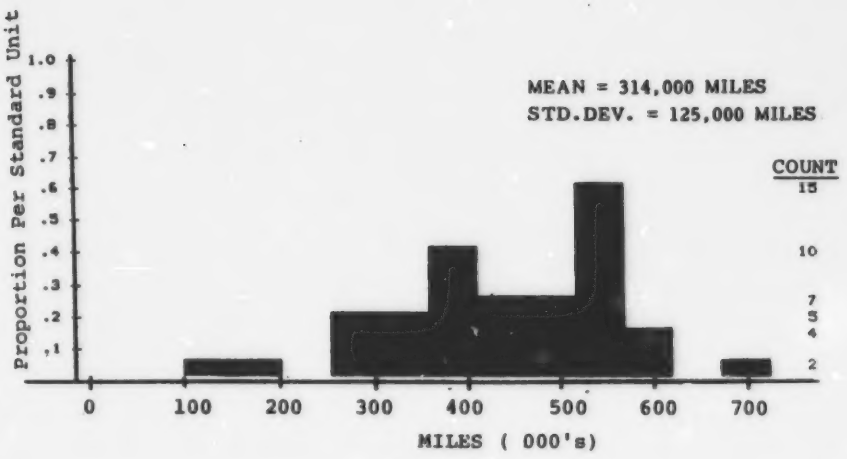

Figure 8 Histogram of high flange failure as a function of mileage - mountainous route

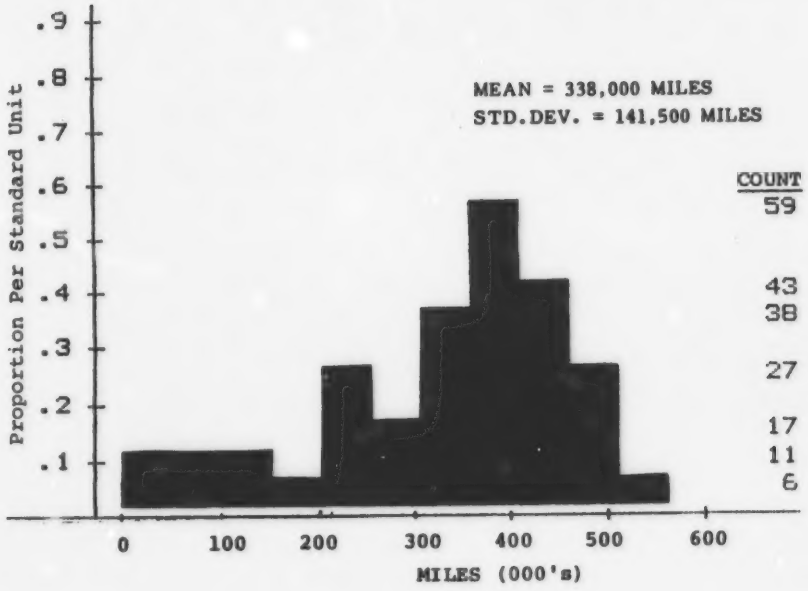

Figure 9 Histogram of high flange failure as a function of mileage -- prairie route

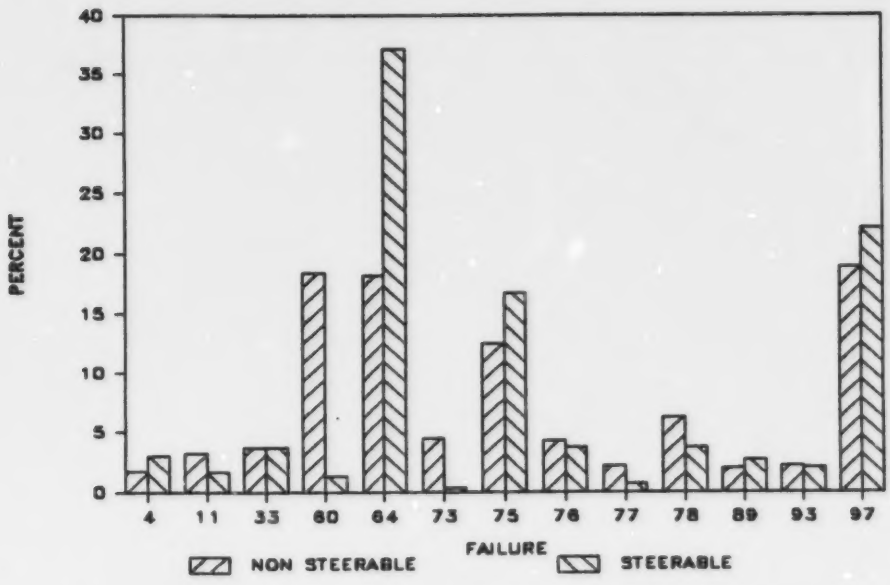

Figure 10 Bar graph of failures for both mountainous and prairie routes

The substantial drop in the incidence of "thin flange" failures for the steerable cars would seem to confirm the efficiency of steerable trucks in reducing flange loading (and thus wear) during operation.

Except for this dramatic drop in thin flange failures, the types of failures have pretty much the same ranking for both sets of cars.

The substantial drop in the incidence of "thin flange" failures for the steerable cars would seem to confirm the efficiency of steerable trucks in reducing flange loading (and thus wear) during operation.

Except for this dramatic drop in thin flange failures, the types of failures have pretty much the same ranking for both sets of cars.

5.2.2 Mileage

Figures 11 and 12 present histograms of all failures as a function of mileage.

The mean mileage between failures of any type is approximately 185,000 miles for steerable cars and drops to 152,000 miles for non-steerable cars, with a remarkably consistent standard deviation of 93,000 miles for both groups.

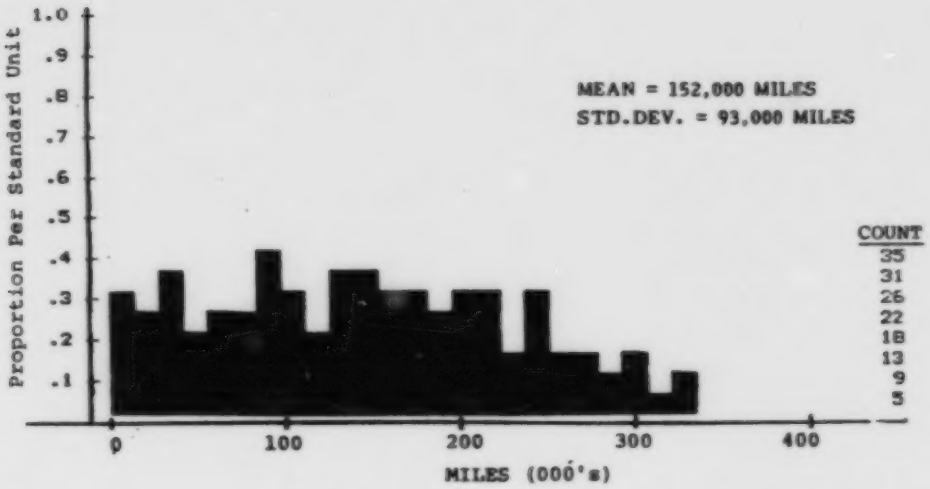

Figure 11 Histogram of all failures as a function of mileage - non-steerable cars

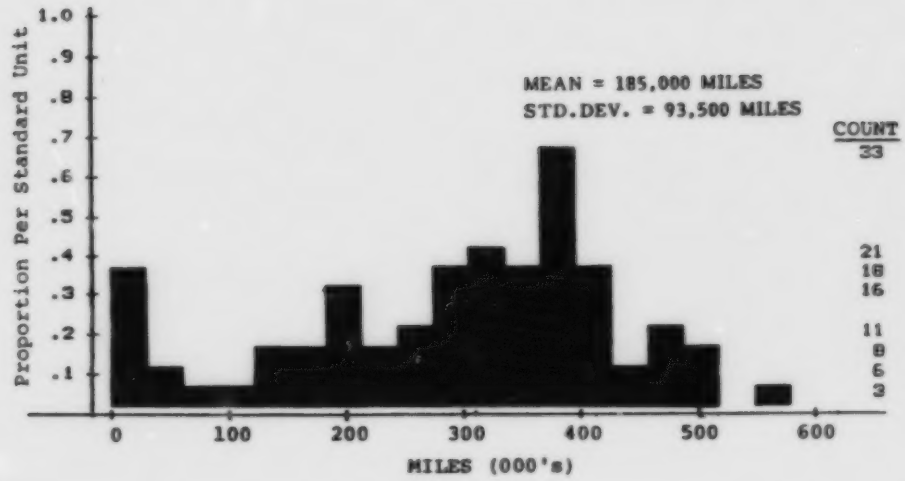

Figure 12 Histogram of all failures as a function of mileage - steerable cars

Such an increase in mean mileage between failures for the steerable cars indicates a significant decrease in wheel-related maintenance for these cars relative to the non-steerable group. This would result in a significant economic benefit, and may justify the use of the rather more expensive steerable trucks.

Considering the individual failure modes, Figures 13 and 14 show histograms for "loose backing ring" for the two groups. The steerable trucks have a mean mileage for failure of this type of 215,000 miles, well above the 169,000 miles for the non-steerable cars. Such a difference would indicate significantly better performance by the steerable trucks for this category of failure.

Figures 15 and 16 show results for "high flange" failure. Again the mean mileage to failure for the steerable cars is much higher and the variation in mileage, as evidenced by the standard deviation, is much smaller than for the non-steerable cars.

Shelling failure results are shown in Figures 17 and 18. The steerable cars again show a greater mean mileage to failure; however, this difference is not significant at the 5 per cent level. This is not unexpected, since shelling is a rolling fatigue failure phenomenon and is not directly controlled by the suspension.

Generally these figures all seem to indicate a greater resistance to failure for wheel sets on steerable trucks. Not only is failure due to thin flange virtually eliminated, all other major failure types occur at increased mileage intervals. If such results can be corroborated for other types of cars, it would indicate that the use of steerable trucks should be seriously considered for a broad range of freight cars.

5.3 Definable Group -- Rolling Element Versus Resilient Side Bearings

In this section results for two nominally identical car groups, except for type of side bearing elements, will be discussed. One group of cars employed rolling element (double roller) side bearings while the other was equipped with resilient side bearings. Both groups of cars were considered to have seen similar operating conditions.

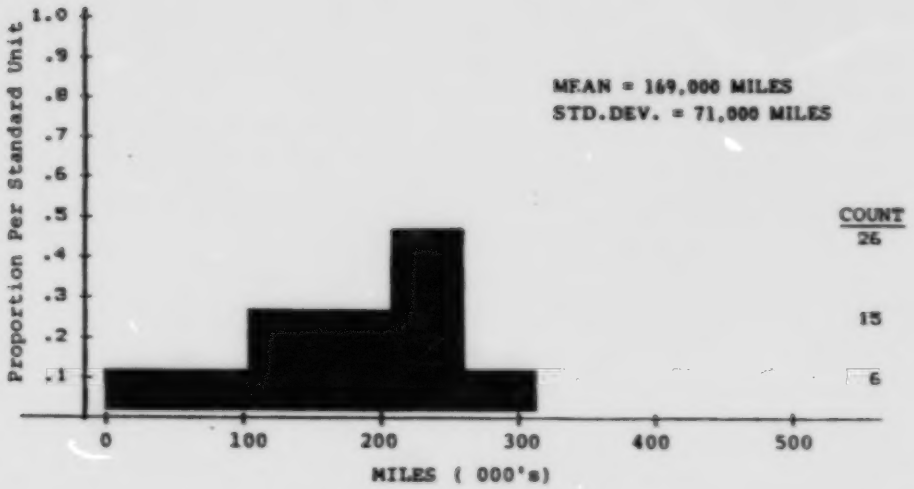

Figure 13 Histogram of loose backing ring failure as a function of mileage - non-steerable cars

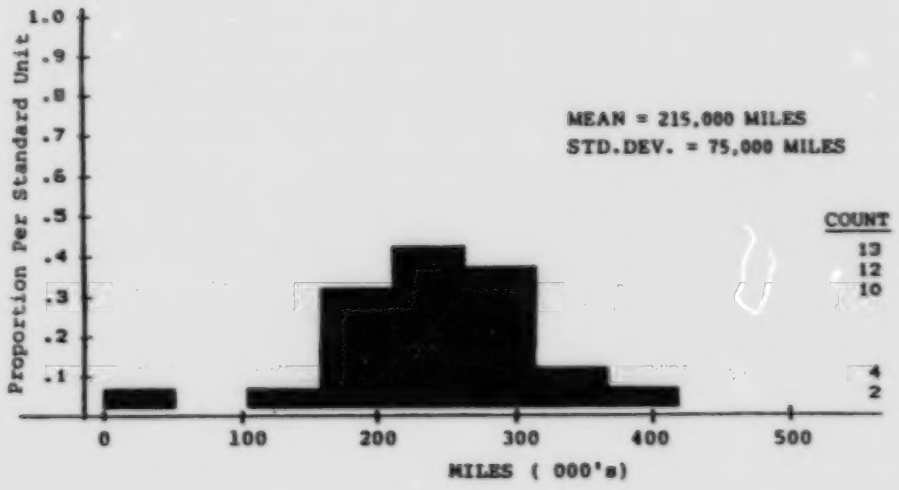

Figure 14 Histogram of loose backing ring failure as a function of mileage - steerable cars

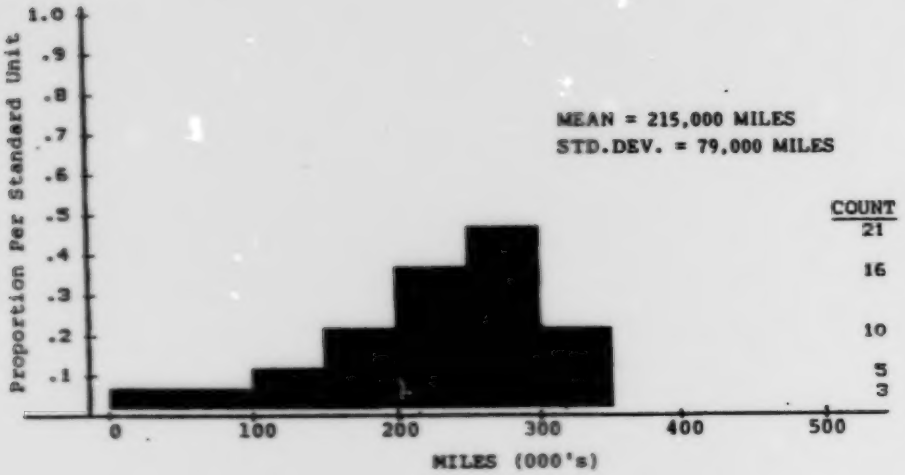

Figure 15 Histogram of high flange failure as a function of mileage - non-steerable cars

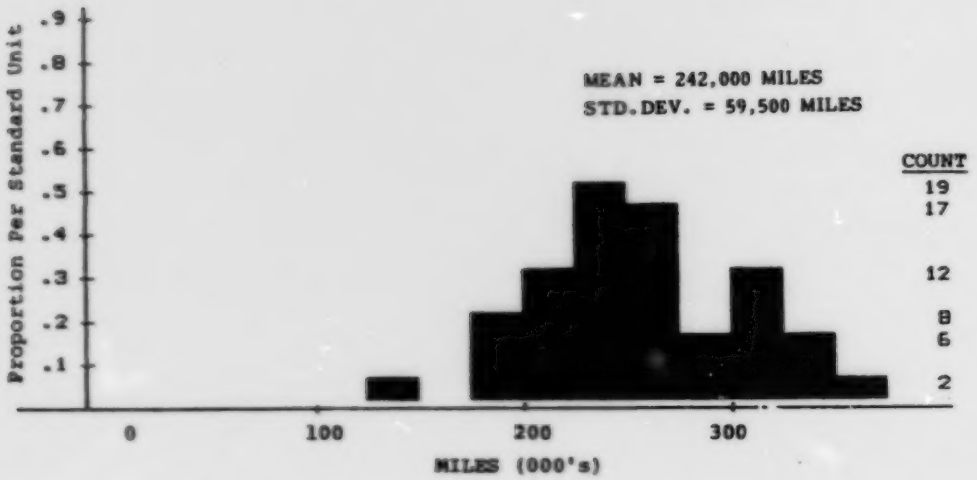

Figure 16 Histogram of high flange failure as a function of mileage - steerable cars

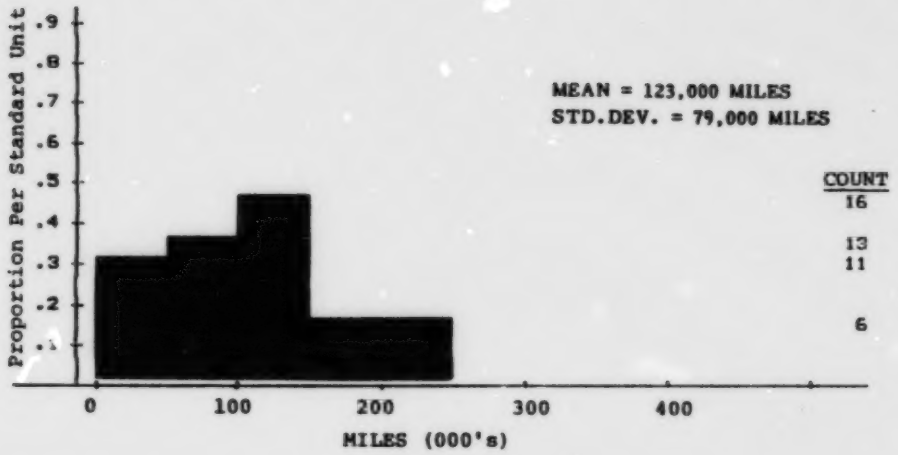

Figure 17 Histogram of shelling failure as a function of mileage - non-steerable cars

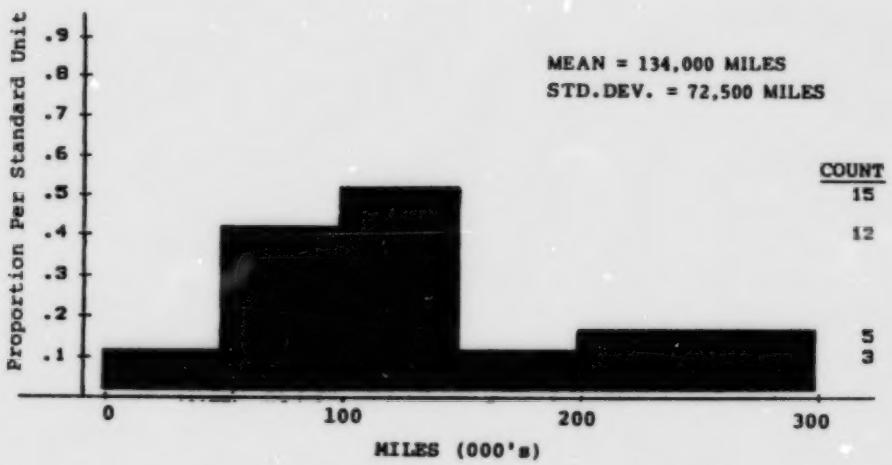

Figure 18 Histogram of shelling failure as a function of mileage - steerable cars

5.3.1 Incidence of Failure

Figure 19 presents a summary bar graph of the incidence of failure for cars equipped with rolling element and resilient side bearings.

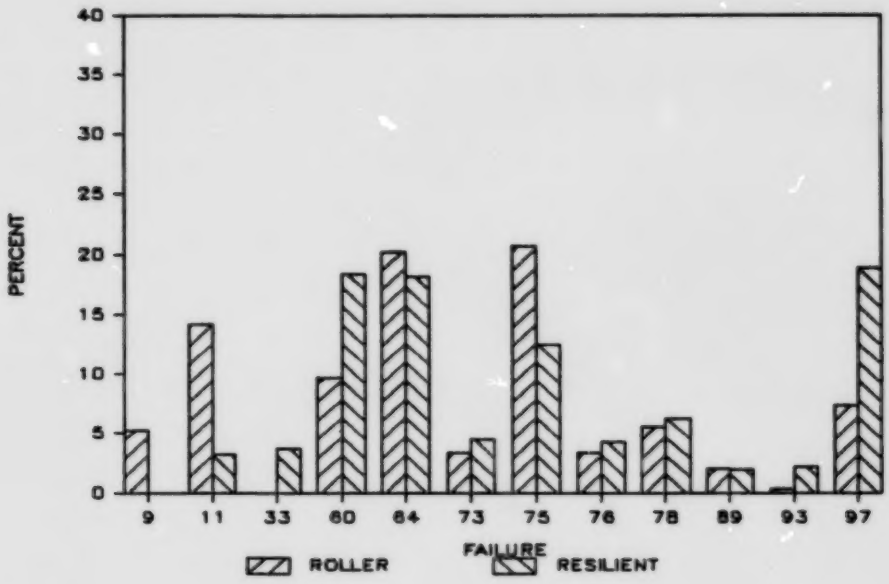

Figure 19 Summary bar graph for cars with rolling element and resilient side bearings

It is apparent from this figure that the incidence of "thin flange" failure is significantly smaller for the rolling element side bearing cars, while the incidence of "high flange" failure is about equal for both groups. Shelling is the prime failure mode for the rolling element cars. The rolling element cars have, however, only about one-third the incidence of "loose backing ring" failures compared to the resilient side bearing cars. The incidence of "associated repair" (code 11) seems unusually higher for the rolling element cars. The reason for this is not clear.

Generally it would seem that use of resilient side bearings reduces the incidence of shelling and has little effect on "high flange" failure incidence. The performance of resilient side bearing cars in the area of "loose backing ring" and "thin flange" failure is decidedly poorer than that of the roller element cars.

5.3.2 Mileage

Figures 20 and 21 present histograms of all failures as a function of mileage.

The mean mileage between failure of any type is 190,000 miles for rolling element side bearings and drops to 152,000 miles for resilent side bearings.

The significantly higher mean mileage between failure for the rolling element side bearing equipped cars indicates a significant decrease in wheel-related maintenance for these cars relative to the resilient side bearing cars. This would seem to provide a significant economic benefit to roller side bearings, at least from a wheel repair point of view, and would suggest that the use of resilient side bearings must be justifiable on some other basis.

Figures 22 and 23 show histograms of "shelling" failures for the two car groups. The rolling element cars have a mean mileage for shelling failure of 179,000 miles. This is well in excess of the 123,000 miles for the resilient bearing cars. This points out that even though shelling failure is the prime reason for wheel repair on the rolling element cars, on the average, a wheelset will give significantly longer service on rolling element cars before suffering a shelling failure.

The results of "loose backing plate" failure are shown in Figures 24 and 25. Again the rolling element bearing cars show better performance with a higher mean mileage to failure.

Figures 26 and 27 present the results for "high flange" failure. The significant difference in mean mileage to failure for the two cases is readily apparent, with the rolling element side bearing cars outperforming the resilient side bearing cars by a wide margin.

The results shown in Figures 28 and 29 compare the performance of the two car groups for "thin flange" failures. As before, the rolling element side bearing cars show a much better mean life between failures.

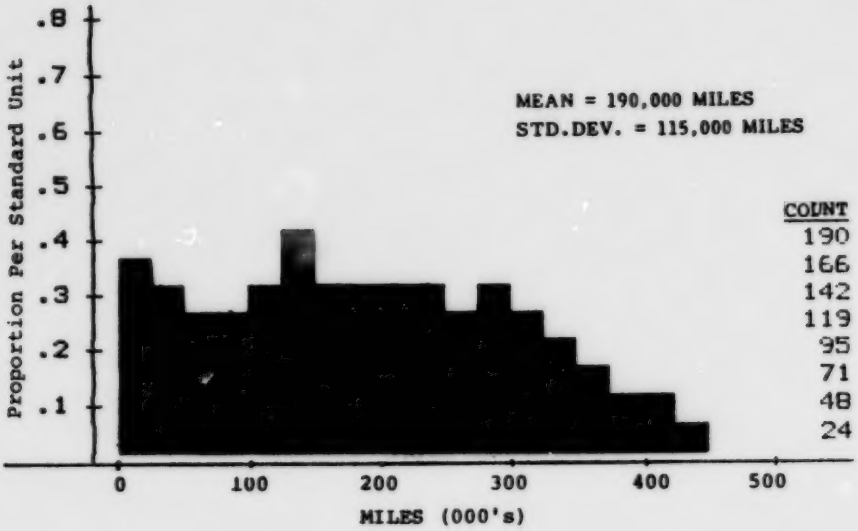

Figure 20 Histogram of all failures as a function of mileage -- rolling element side bearings

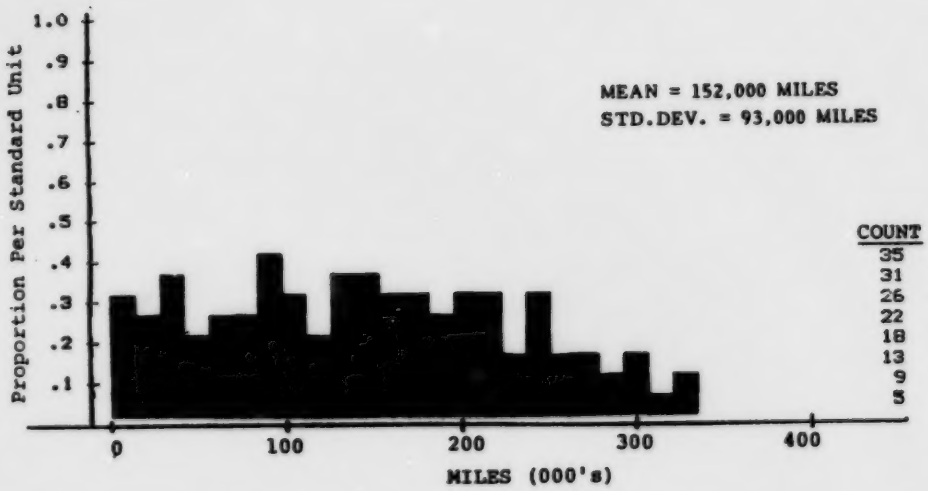

Figure 21 Histogram of all failures as a function of mileage -- resilient side bearings

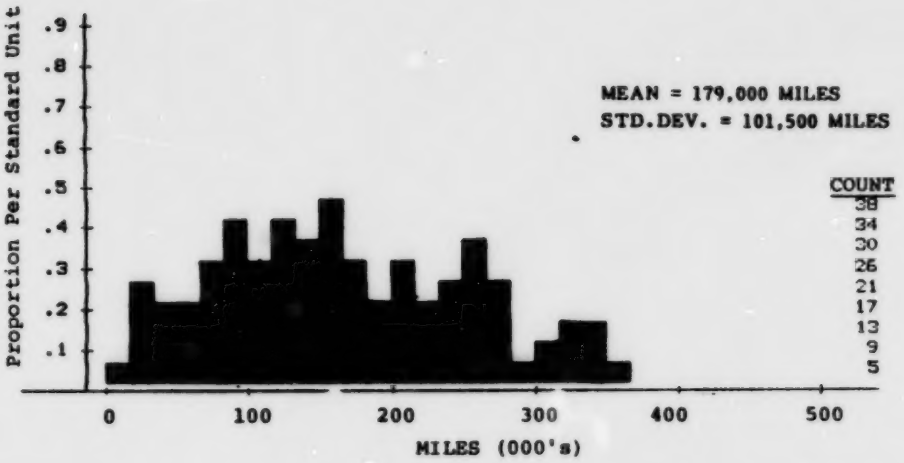

Figure 22 Histogram of shelling failures as a function of mileage -- rolling element side bearings

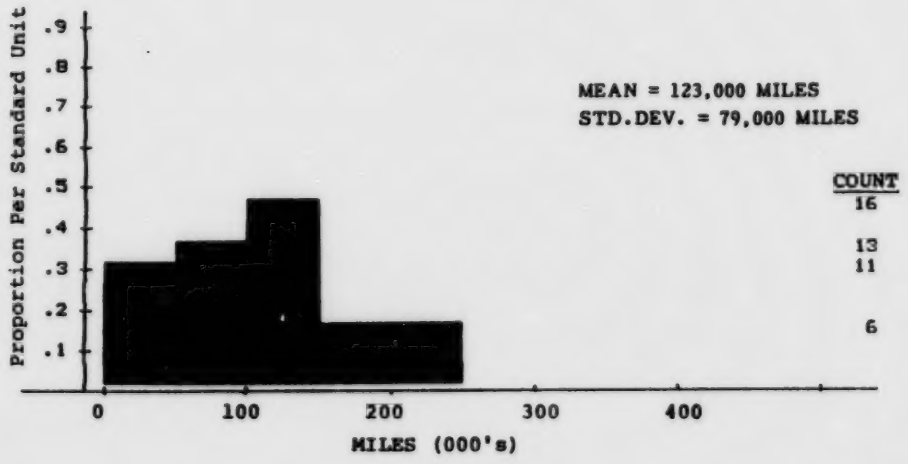

Figure 23 Histogram of shelling failures as a function of mileage -- resilient side bearings

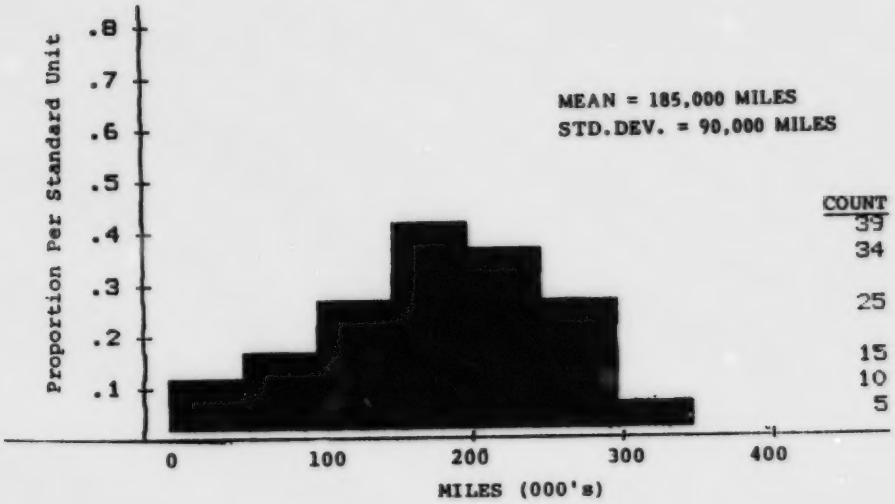

Figure 24 Histogram of loose backing ring as a function of mileage -- rolling element side bearings

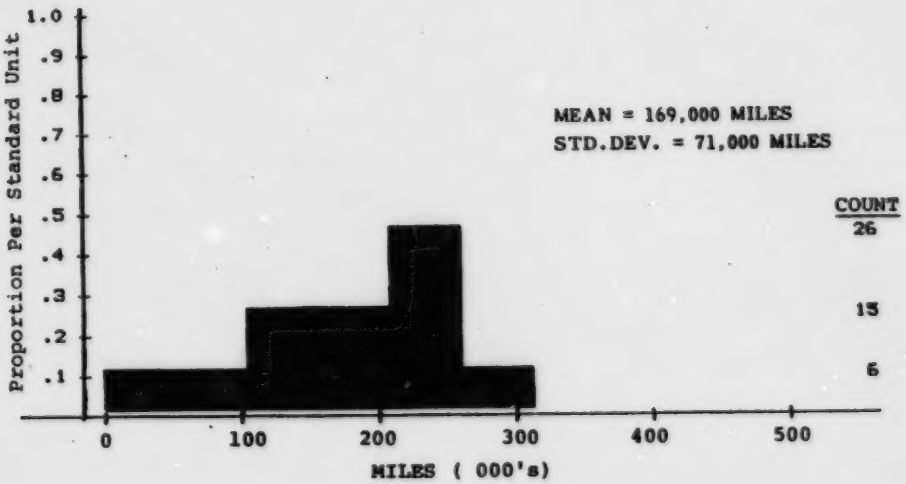

Figure 25 Histogram of loose backing ring as a function of mileage -- resilient side bearings

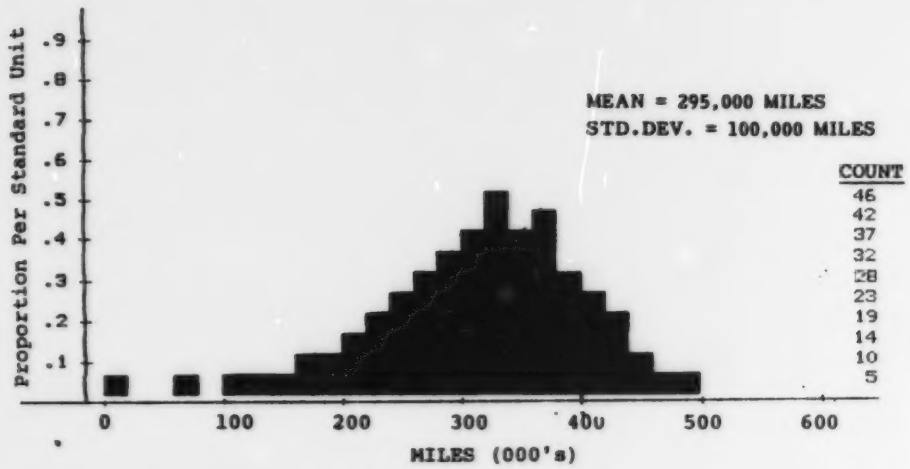

Figure 26 Histogram of high flange failure as a function of mileage -- rolling element side bearings

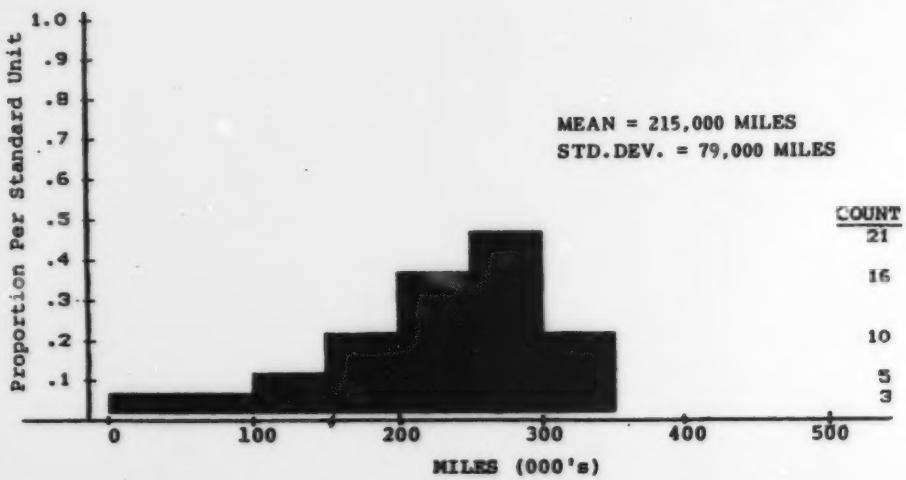

Figure 27 Histogram of high flange failure as a function of mileage -- resilient side bearings

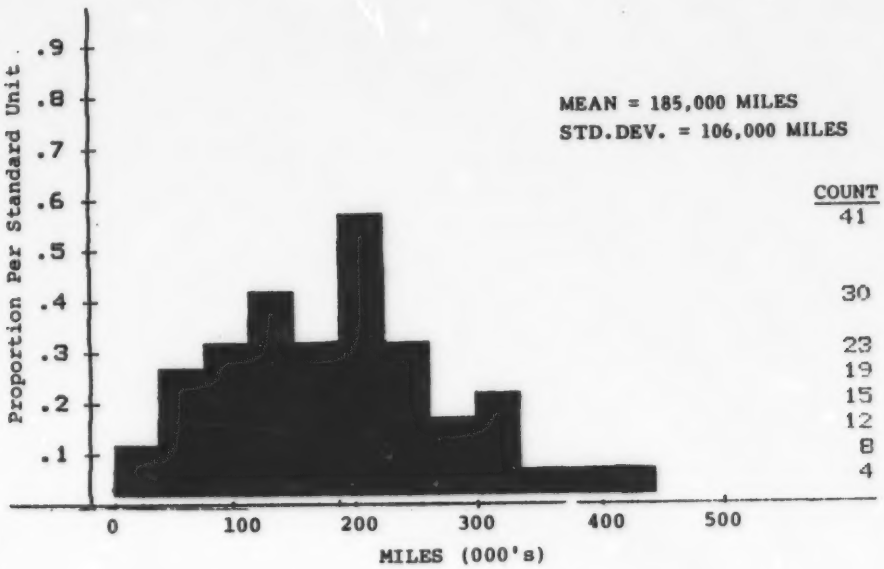

Figure 28 Histogram of thin flange failure as a function of mileage -- rolling element side bearings

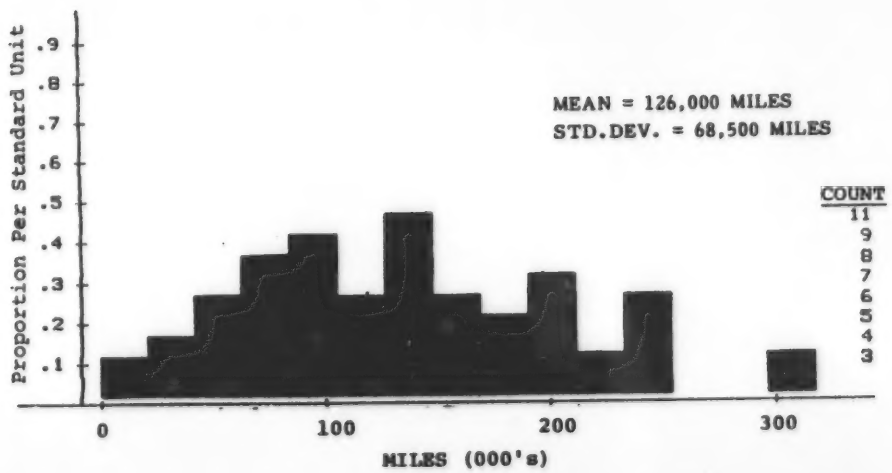

Figure 29 Histogram of thin flange failure as a function of mileage -- resilient side bearings

As noted earlier, it seems evident that the rolling element side bearings certainly provide better service from the point of view of life between wheel failures. This would translate into reduced wheel replacement costs and should make the rolling element side bearing the preferred configuration. Of course, it may well be that resilient side bearings produce other benefits, not directly related to wheel life, that may justify their use. If, however, this is not the case, then it would seem wise to investigate the possibility of reverting to rolling element side bearings where possible.

5.4. Wheel Failure Monitoring

Up to this point the available wheel replacement data base has been used to investigate the effects of various parameters on the type and frequency of wheel failures.

At this point it should be noted that the development of an "on-line" wheel replacement data base that produces simple, yet descriptive, graphical outputs could become a valuable tool for both engineering and maintenance personnel.

The type of system envisaged would use remote terminals to provide access to a "Wheel Failure Reporting Systems" (WFRS). The terminals could be placed in engineering office locations and also at all maintenance locations where freight car wheel repair is performed. The WFRS would provide statistics on single cars or desired groupings of cars.

With such a system, Engineering could monitor the effect of a particular design modification on wheel failure rate. Important trends could quickly be discerned and appropriate follow-up action could be initiated.

Maintenance supervisory personnel could see the effect of changes in maintenance procedures and make necessary adjustments. Also, with on-line wheel failure records it would become possible to begin a preventive (and, potentially, a predictive) maintenance approach for wheelsets. As an example, a freight car may be brought in to a maintenance depot for a shattered rim on wheelset #1. With the WFRS available, the maintenance personnel could call up the wheel replacement records for

the particular car in question. The maintenance history for all the wheelsets on the car would then be reviewed. If, say, wheelset #4 is found to be one standard deviation beyond the mean failure mileage for shelling, then this wheelset would also be replaced. This would prevent the situation where wheelset #1 is replaced because of the shattered rim and then the car is placed in service only to be removed again a few days, or weeks, later for a shelling failure on wheelset #4. A number of examples of such rapid return of a car for subsequent repairs were found in the wheel replacement data base available for this study. Obviously, such preventive maintenance procedures could be very beneficial, not only from the immediate economic gains but also from the point of view of much higher car availability factors.

Figure 30 shows the type of monitoring information that might be generated for a particular group of cars. In this instance a series of bar graphs representing the types of failures, and their percentage occurrence, for a number of years, is shown. These yearly values could be compared among themselves to determine if any unusually high (or low) failure rates are experienced. Also, each yearly output could be compared to a long-term record summary, as shown in Figure 31, to see if significant variations are apparent. Appropriate action could then be taken on the basis of judgments made from these comparisons.

As an example, notice from the yearly records that failures due to loose backing ring (code 97) have been increasing since 1980. This would indicate that some judgment should be made on possible remedial measures.

As another example, shelling incidences have been consistently around 10 per cent for the first three years shown. However, the last two years have shown a small, but definite, rise in incidence. Obviously data for the year 1985 would be reviewed to see if the trend continues, and if so, action would be taken to prevent a continued rise in this failure category.

In some cases it may be desirable to look at shorter time periods than years. Figures 32 and 33 show monthly records for two different car groups.

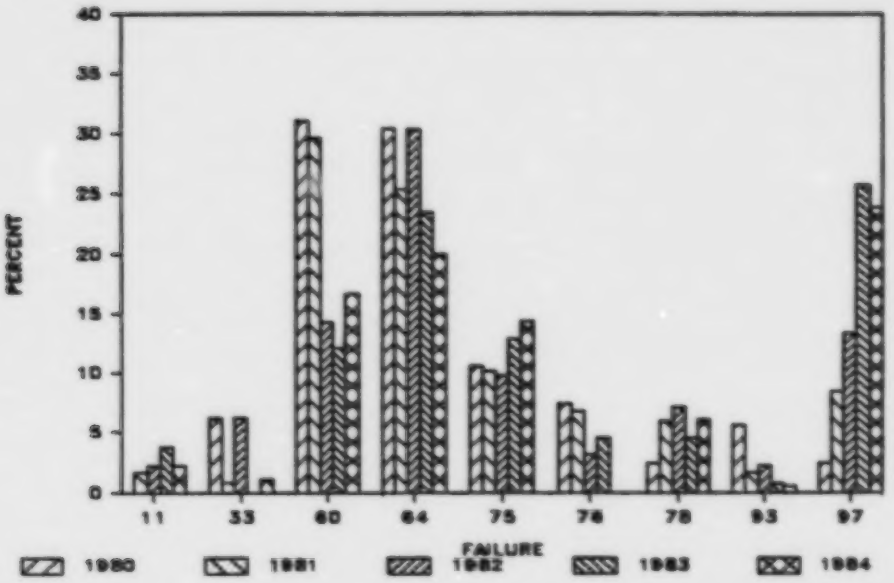

Figure 30 Example of a possible wheel failure monitoring system output - by year

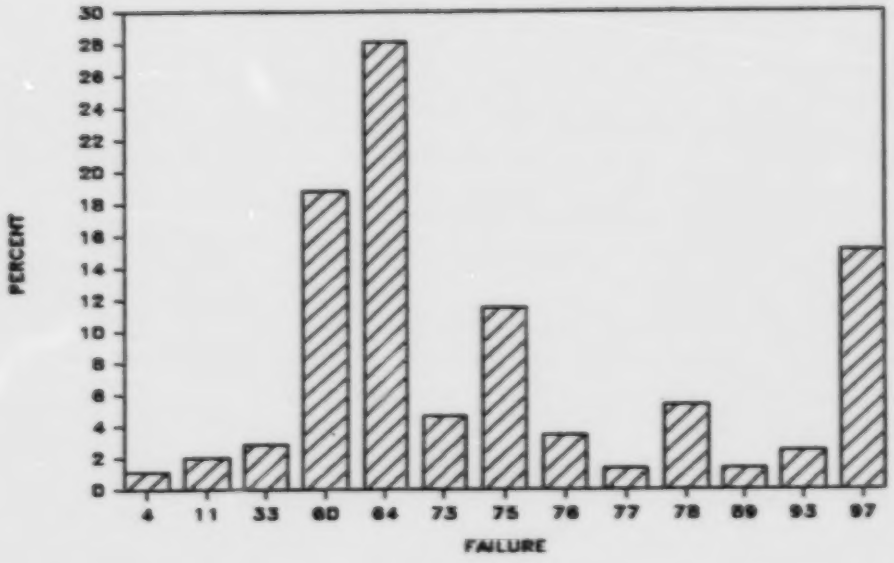

Figure 31 Example of a possible wheel failure monitoring system output - long-term summary

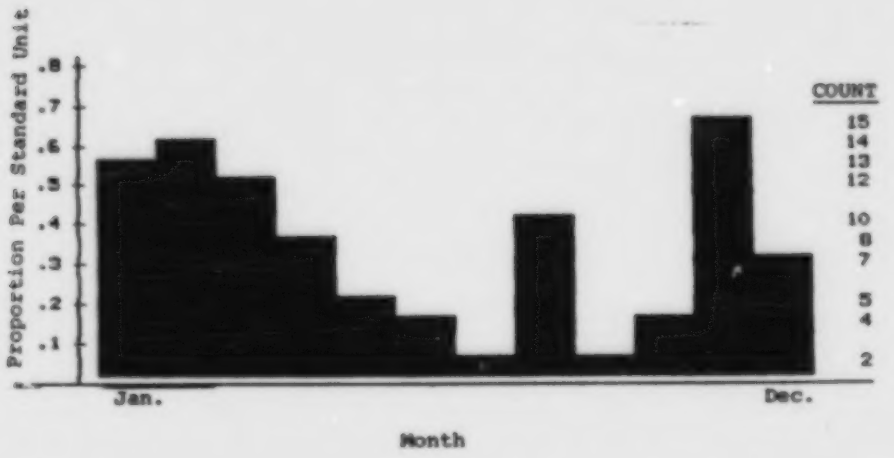

Figure 32 Histogram of failures by month -- non-steerable cars

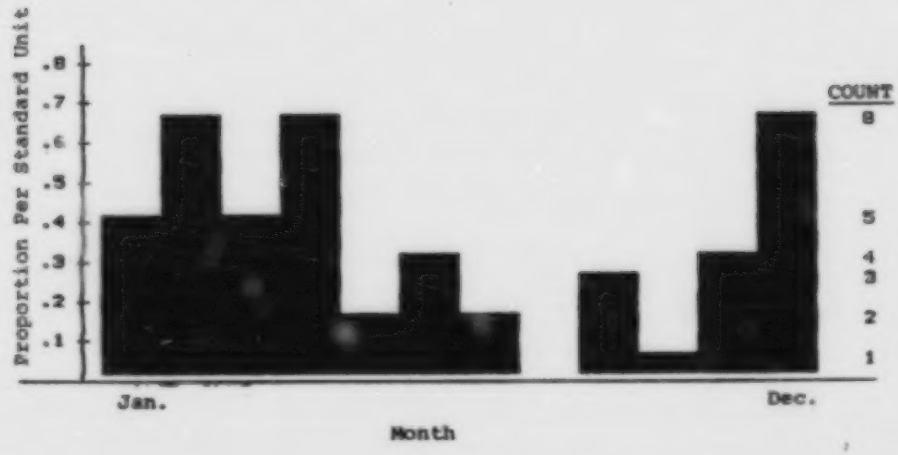

Figure 33 Histogram of failures by month -- steerable cars

Such monthly records not only highlight anomalies in short-term wheel replacement incidence but also help to establish possible seasonal variations for particular wheel failures. Such information, coupled with knowledge of average monthly mileage and mean mileage for a particular type of failure, could be a very valuable aid in determining strategies to minimize the disruptive effect of wheel failures on freight movement.

6. CONCLUSION

This study has reviewed available wheel defect data bases for particular coal trains in an effort to identify those defects which most contribute to system wheel cost and also to isolate the factors which contribute to such failures.

The following general conclusions can be drawn from the data presented in this report and from the experience gained in working with the available wheel defect data bases.

- The data reviewed in this study clearly indicates the large variability in wheel life experienced by nominally identical wheels running under essentially identical operating conditions as parts of a unit coal train. Standard deviations of the order of 75,000 to 100,000 miles for a particular type of wheel defect were not unusual.

- When the data was grouped by type of route travelled (mountainous versus prairie), it was found that significant differences occurred in the relative incidence of particular failure types as a function of route. However, the most prevalent failure type for both routes was shelling. Its incidence was not significantly different for the two types of routes. No conclusion could be drawn as to the exact cause of these findings. Significantly more data would be required to isolate particular contributing factors.

- When the car data was grouped by steerable versus non-steerable truck, several interesting trends became evident. To begin, the incidence of failure due to "thin flange" dropped dramatically for the steerable truck equipped cars. Also the mean mileage between failures for any particular failure type generally increased significantly. This means that the steerable trucks can be considered to reduce wheel failure.

- Review of the available data for rolling element side bearing and resilient element side bearing equipped cars showed that, for the cars studied, the rolling element side bearings provided significantly better performance in terms of extending wheel life.

- The present study was unable to isolate particular factors as being the cause of particular types of wheel failure. This study was not designed to obtain such results, since significantly more data would be necessary than that generally recorded in the railways' wheel replacement data bases.

- The potential benefits of a Wheel Failure Reporting System were reviewed and examples were provided of the type of summary statistics that might be generated by such a system.

- It is felt that this preliminary study has indicated that it is both practical, and potentially beneficial, to undertake further statistical studies on a larger scale. A study focused on a particular unit train route, but with the available data expanded to include macro and micro aspects of the wheels and track, suspension system details, car loading, weather conditions, etc., would be of great benefit. In this manner emphasis could be placed on car-to-car differences rather than the large-scale differences such as route. Thus, the particularly vexing large variations in wheel life for supposedly identical conditions could be tackled directly.

  Also, effort should be expended on the development of a computer-based Wheel Failure Reporting System. This on-line system would provide summary statistics, generally in graphic format, to aid in the evaluation of engineering design changes and maintenance functions. Particular emphasis should be placed on determining the type of statistics to be presented by such a system and the most useful graphical formats.

BIBLIOGRAPHY

Andrews, H.I. "The Contact Between Locomotive Driving Wheel and the Rail." Wear, Vol. 2, pp. 468-484 (1958/59).

Beagley, T.M. "Severe Wear of Rolling/Sliding Contacts." Wear, Vol. 36, pp. 317-335 (1976).

Brickle, Gilchrist. "A Re-examination of the Proneness to Derailment of a Railway Wheelset." JMES, Vol. 18, pp. 131-141 (1977).

Bruner, J.P., D.M. Bench, G.N. Benjamin. "Analysis of Residual, Thermal, and Loading Stresses in a 833 Wheel and Their Relationship to Fatigue Damage." ASME, Anthology or Rail Vehicle Dynamics, Vol. III, pp. 174-183 (1973).

Bruner, J.P., R.D. Jones, S. Levy, J.M. Wandrisco. "Effect of Design Variation on Service Stresses in Railroad Wheels." ASME, Anthology of Rail Vehicle Dynamics, Vol. III, pp. 185-195 (1973).

Clark, Dean, Elkins, Newton. "An Investigation into the Dynamic Effects of Railway Vehicles Running on Corrugated Rails." JMES, Vol. 24, pp. 65-76 (1982).

Clark, R.A., S.G. Newton. "An Investigation into the Dynamic Effects on the Track of Wheelflats on Railway Vehicles." JMES, Vol. 21, pp. 287-297 (1979).

Dearden, J. "The Wear of Steel Rails and Tyres in Railway Service." Wear, Vol. 3, pp. 43-59 (1960).

Decuyper, M. "Geometry of Wheel-Rail Contact: Extended Envelope Method." International Journal of Vehicle Design, Vol. 4, pp. 36-52 (1983).

Dewez, F.J., J.M. Wandrisco. "Study of the Defects that Originate and Develop in the Treads of Railroad Wheels During Service." ASME, Anthology of Rail Vehicle Dynamics, Vol. III, pp. 79-90 (1973).

Duffek, W., A. Jaschinski. "Efficient Implementation of Wheel-Rail Contact Mechanics in Dynamic Curving (Extensive Summary)." Vehicle System Dynamics, Vol. 10, pp. 184-192 (1981).

Evensen, Kaplan. "Some Problems of Wheel-Rail Interaction Associated with High-Speed Trains." Bulletin of the Int. Railway Const. Ops., Vol. 46, pp. 513-541.

Fec, M.E., H. Sehitoglu. "Thermal-Mechanical Damage in Railroad Wheels Due to Hot Spotting." Wear, Vol. 102, pp. 31-42 (1985).

Garcia-Vadillo, E., J.G. Gimenez, J.A. Tarrago. "Wheel/Rail Contact: Geometrical Study." Vehicle System Dynamics, Vol. 13, pp. 207-214 (1984).

Grassie, S.L., K.L. Johnson. "Periodic Microslip Between a Rolling Wheel and a Corrugated Rail." Wear, Vol. 101, pp. 291-309 (1985).

Grassie, S.L., R.W. Gregory, D. Harrison, K.L. Johnson. "The Dynamic Response of Railway Track to High Frequency Vertical Excitation." JMES, Vol. 24, pp. 77-90 (1982).

Grassie, S.L., R.W. Gregory, D. Johnson. "The Behaviour of Railway Wheelsets and Track at High Frequencies of Excitation." JMES, Vol. 24, pp. 103-111 (1982).

Grassie, S.L., R.W. Gregory, D. Johnson. "The Dynamic Response of Railway Track to High-Frequency Longitudinal Excitation." JMES, Vol. 24, pp. 97-102 (1982).

Grassie, S.L., R.W. Gregory, D. Johnson. "The Dynamic Response of Railway Track to High Frequency Lateral Excitation." JMES, Vol. 24, pp. 91-95 (1982).

Jamison, W.E. "The Wear of Railroad Freight Car Wheels and Rails." Lubrication Engineering, Vol. 36, No. 7, pp. 401-410 (1980).

Jennings, J.R. "Relation to Wheel Tread Wear and Brake Shoe Wear." ASME, Anthology of Rail Vehicle Dynamics, Vol. III, pp. 92-101.

Johnson, M.R. "Development of Fatigue Standards for Freight Car Truck Components and Wheels." ASME 1974 Rail Transport Proceedings. ASME Paper #74-RT-4, 13 p. (1974).

Kalker, J.J. "Survey of Wheel-Rail Rolling Contact Theory." Vehicle System Dynamics, Vol. 8, pp. 317-358 (1979).

Keizer, C.P. "Some Basic Properties of Bogies, An Analytical Approach." Vehicle System Dynamics, Vol. 8, pp. 359-406 (1979).

Kilburn, K.R. "An Introduction to Rail Wear and Rail Lubrication Problems." Wear, Vol. 7, pp. 255-269 (1964).

Krause, H., E. ÖCalan. "Investigation of the Relationship Between the Stresses at the Rolling or the Rolling-Sliding Contact and the Texture Development in the Proximity of the Surface of Wheels and Rails and Their Interpretation With Model Tests." Wear, Vol. 79, pp. 295-300 (1982).

Lohe, M.A., R.R. Huilgol. "Flange Force Effects on the Motion of a Train Wheelset." Vehicle System Dynamics, Vol. 11, pp. 283-303 (1982).

McLean, L.A. "Engineering for Maintenance-Fee Freight Cars." ASME 1972 Rail Transport Proceedings. ASME Paper #72-RT-4, 19 p. (1972).

Mitura, K., P. Matusek, R. Faja. "Intensive Braking as the Cause of Thermal Damaging of Railway Wheels." Rail International, Vol. 12, pp. 306-317 (1981).

Newland, D.E. "On the Time Dependent Spin Creep of a Railway Wheel." JMES, Vol. 24, pp. 55-64 91982)

Nishimura, S., K. Tokimasa. "Study on the Residual Stresses in Railroad Solid Wheels and Their Effect on Wheel Fracture." Bulletin of the JSME, Vol. 19, No. 131, pp. 459-468 (1976).

Nishimura, S., Y. Morita, K. Tokimasa. "An Improved Method for Measuring the Residual Stresses in Railroad Solid Wheels." Bulletin of the JSME, Vol. 18, No. 116, pp. 114-122 (1975)

Nishioka, K., Y. Morita. "The Strength of Railroad Wheels." Bulletin of the JSME, Vol. 13, No. 64, pp. 1165-1171 (1970).

Nishioka, K., Y. Morita. "The Strength of Railroad Wheels." Bulletin of the JSME, Vol. 12, No. 52, pp. 738-746 (1969).

Novak, G.E., B.J. Eck. "A Three-Dimensional Finite Difference Solution for the Thermal Stresses in Railcar Wheels." ASME, Anthology of Rail Vehicle Dynamics, pp. 197-203 (1973).

O'Regan, S.D., G.T. Hahn, C.A. Rubin. "The Driving Force for Mode II Crack Growth Under Rolling Contact." Wear, Vol. 101, pp. 333-346 (1985).

Palhan, R.K. "Design Considerations for Minimizing Wear in Railway Operation." Wear, Vol. 80, pp. 133-148 (1982).

Peterson, L.A., W.H. Freeman, J.M. Wandrisco. "Measurement and Analysis of Wheel-Rail Forces." ASME 1972 Rail Transport Proceedings, ASME Paper #71-WA/RT-4, 24 p. (1972).

Piotrowski, J. "A Theory of Wheelset Forces for a Two-Point Contact Between Wheel and Rail." Vehicle System Dynamics, Vol. 11, pp. 69-87 (1982).

Rail International. "Geometry of the Contact Between Wheelset and Track. Vol. 5, Communications of ORE, pp. 252-256 (1974).

Remington, P.J. "Wheel/Rail Noise - Part I: Characterization of the Wheel/Rail Dynamic System." Journal of Sound and Vibration, Vol. 46, pp. 359-379 (1976).

Reynolds, D.J. "Hunting in Freight Cars." ASME 1974 Rail Transport Proceedings. ASME Paper #74-RT-2, 15 p. (1974).

Scheffel, H. "A New Design Approach for Railway Vehicle Suspension." Rail International, Vol. 5, pp. 638-651 (1974).

Taylor, A.O. "Measurement of Freight Car Wheel Quality." ASME 1972 Rail Transportation Proceedings, ASME Paper #72-RD-5, 14 p. (1972).

Tyler, H.A. "Wheel Mileage Performance on Ore Cars Operating Over the Quebec North Shore and Labrador Railway." ASME, Anthology of Rail Vehicle Dynamices, Vol. III, pp. 108-118 (1973).

APPENDIX A

SYSTAT

SYSTAT, from Systat Inc., Evanston, Illinois, is a command-driven package for statistical analysis which runs under MS-DOS. It consists of eleven FORTRAN modules on six disks, and offers a wide breadth of options. Each of the modules has an adequate on-line help facility.

THE MODULES

1. DATA Module

   - Full screen editor, which looks like a spreadsheet (rather slow to use). It can handle a file as large as a disk can hold.
   - Data may be input free or formatted, from the keyboard or an ASCII file. (The manual explains how to produce SYSTAT-readable files using LOTUS 1-2-3, dBASE II, and dBASE III).
   - The BASIC programming language is used for data manipulation.
   - Can merge, join, and subset multiple files, by one or more variables. (The manipulation of columns and files is somewhat less convenient than MINITAB and MICROSTAT but neither of these has the editor or the power of BASIC for data manipulation.)

2. GRAPH Module

   - Standard X-Y points, histograms, multiple box-plots, stem-and-leaf plots, normal and half-normal plots (both can be detrended), cumulative frequency plots, and quantile-quantile plots.
   - Like output from the other modules, graphics can be saved into disk files for use in word processors, if necessary.

3. STATS Module

   - Computes all statistics in double precision using provisional means and sums of squares algorithms.
   - Statistics on a single column of data; one-way ANOVA and two-group t-tests using BY command.
   - Exact critical values for multiple comparisons (Tukey, Duncan, and Newman-Keuls).

4. TABLES Module

   . Frequency tabulation in one- to n-way tables (with options for percentages).

   . Log-linear models with residuals and goodness-to-fit tests (Pearson and likelihood ratio).

5. CORRELATION Module

   . Choice of several pairwise association measured for sets of variables (can be stored in a matrix for use in later modules). Sums of squares, covariance, Pearson correlations, Spearman, Kendal's tau rank correlations, and Euclidean, gamma, and mu^2.

6. MULTIVARIATE GENERAL LINEAR HYPOTHESIS (MGLH) Module

   . Each procedure can store residuals and influence statistics for later graphical analysis. As well as specifying a model and estimating its parameters, a process which gives the approporiate (fixed-effects) analysis of variance table, the module has a series of commands which test hypotheses about linear contrasts and do other, more sophisticated things.

   . Features: multiple linear regression, stepwise regression, unbalanced n-way ANOVA, multivariate ANOVA (giving a variety of test statistics), repeated measures, nested designs, multivariate regression, discriminant analysis, canonical correlation.

7. FACTOR ANALYSIS Module

   . Principal components (with loading plots and rotations).

8. MULTIDIMENSIONAL SCALING (MDS) Module

   . Kruskal and Guttman methods, plots Shepard diagrams.

9. CLUSTER ANALYSIS Module

   . Hierarchical tree, linkage, and k-means splitting methods; prints cluster dendograms.

10. NONPARAMETRIC Module

   . Sign, Wilcoxon signed rank, Mann-Whitney U, Kruskal-Wallis, Friedman, Kolomogorov-Smirnov one sample (normal uniform and chi-square options) or two sample.

11. TIME SERIES Module

   . Smoothing, plotting, ARIMA, Fourier analysis, and forecasting.

APPENDIX B

AAR "WHY MADE" CODES

03 - Missing
07 - Obsolete Material
08 - Wrong (not standard to car)
09 - Account Repairs
11 - Removed in Good Condition Account of Associated Repairs
25 - Owner's Request
31 - Fire or Heat Damage per Rule 95
32 - Flood Damage per Rule 95
33 - Derailment Damage per Rule 95
34 - Unfair Usage Damage per Rule 95 (other than fire, flood, or derailment)
40 - Journal Cracked or Broken
50 - Journal and Rolling Bearing Overheated, Periodic Lubrication less than 30 Days Overdue (includes bearings and requiring field lubrication)
51 - Journal and Roller Bearing Overheated, Periodic Lubrication 30 or More Days Overdue, no Date on Car or Date Illegible
54 - Axle Broken or Cracked (cold)
55 - Axle Damaged Between Wheelsets 1/8 Inch or Deeper
56 - Axle with Evidence of Welding
59 - Axle Bent
60 - Thin Flange
62 - Vertical Flange
64 - High Flange
66 - Cracked or Broken Flange
68 - Cracked or Broken Rim
70 - Burnt Rim
71 - Shattered Rim
72 - Spread Rim
73 - Thin Rim
74 - Thermal Cracks
75 - Shelled Tread
76 - Built-Up Tread
77 - Grooved Tread
78 - Tread Slid Flat
79 - Tread Slid Flat with Flange Wear or Tread Wear
80 - Scrape, Dent or Gouge in Wheel Plate
81 - Wheel Out of Gauge
82 - Wheel with Cracked Hub
83 - Wheel with Cracked or Broken Plate
84 - Wheel with Holes in Plate
85 - Wheel Loose
89 - Wheel Overheated Due to Stuck or Dragging Brake
92 - Loose Cap Screw
93 - Loose or Defective Seals
94 - Welding Arcing Damage
95 - Roller Bearing Fused Due to Overheating, Periodic Lubrication Less than 30 Days Overdue (includes bearings not requiring field lubrication)
96 - Roller Bearing Fused Due to Overheating, Periodic Lubrication 30 or More Days Overdue, No Date on Car or Date Illegible
97 - Loose Backing Ring

APPENDIX C

BAR GRAPH SUMMARY STATISTICS

TABLE C.1

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE"
CODE - MOUNTAINOUS ROUTE

VALUE	COUNT	PERCENT
8.000	1	.05
11.000	8	.39
33.000	38	1.83
40.000	1	.05
50.000	9	.43
55.000	3	.14
60.000	250	12.07
62.000	14	.68
64.000	62	2.99
66.000	13	.63
68.000	8	.39
72.000	1	.05
73.000	10	.48
74.000	2	.10
75.000	1212	58.49
76.000	67	3.23
77.000	3	.14
78.000	140	6.76
79.000	1	.05
81.000	1	.05
89.000	2	.10
92.000	3	.14
93.000	61	2.94
94.000	1	.05
95.000	3	.14
97.000	158	7.63

TABLE C.2

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE" CODE - PRAIRIE ROUTE

VALUE	COUNT	PERCENT
3.000	31	.58
8.000	11	.21
9.000	1	.02
11.000	83	1.56
25.000	28	.53
33.000	97	1.83
50.000	6	.11
51.000	1	.02
55.000	5	.09
56.000	1	.02
60.000	701	13.19
62.000	27	.51
64.000	290	5.46
66.000	19	.36
68.000	16	.30
71.000	2	.04
72.000	99	1.86
73.000	29	.55
74.000	5	.09
75.000	2760	51.93
76.000	57	1.07
77.000	2	.04
78.000	96	1.81
83.000	1	.02
85.000	1	.02
89.000	1	.02
92.000	17	.32
93.000	65	1.22
94.000	1	.02
95.000	4	.08
96.000	2	.04
97.000	856	16.11

TABLE C.3

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE" CODE - NON-STEERABLE CARS

VALUE	COUNT	PERCENT
4.000	10	1.78
11.000	18	3.21
33.000	21	3.74
44.000	1	.18
50.000	4	.71
60.000	103	18.36
64.000	102	18.18
68.000	1	.18
71.000	1	.18
72.000	1	.18
73.000	25	4.46
75.000	70	12.48
76.000	24	4.28
77.000	12	2.14
78.000	35	6.24
80.000	1	.18
85.000	1	.18
89.000	11	1.96
92.000	2	.36
93.000	12	2.14
97.000	106	18.89

TABLE C.4

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE" CODE - STEERABLE CARS

VALUE	COUNT	PERCENT
4.000	9	3.01
11.000	5	1.67
33.000	11	3.68
50.000	4	1.34
60.000	4	1.34
64.000	111	37.12
73.000	1	.33
75.000	50	16.72
76.000	11	3.68
77.000	2	.67
78.000	11	3.68
89.000	8	2.68
93.000	6	2.01
97.000	66	22.07

TABLE C.5

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE" CODE - ROLLING ELEMENT SIDE BEARING

VALUE	COUNT	PERCENT
0.000	1	.04
1.000	2	.09
2.000	2	.09
3.000	68	3.02
4.000	9	.40
7.000	1	.04
9.000	119	5.29
11.000	318	14.14
31.000	3	.13
32.000	1	.04
60.000	218	9.69
63.000	2	.09
64.000	454	20.19
66.000	3	.13
68.000	5	.22
71.000	3	.13
72.000	2	.09
73.000	75	3.33
74.000	6	.27
75.000	465	20.68
76.000	75	3.33
77.000	18	.80
78.000	124	5.51
79.000	23	1.02
83.000	1	.04
89.000	46	2.05
90.000	6	.27
93.000	7	.31
96.000	3	.13
97.000	166	7.38
98.000	9	.40
99.000	14	.62

TABLE C.6

SUMMARY OF FAILURE INCIDENCE BY "WHY MADE"
CODE - RESILIENT SIDE BEARINGS

VALUE	COUNT	PERCENT
4.000	10	1.78
11.000	18	3.21
33.000	21	3.74
44.000	1	.18
50.000	4	.71
60.000	103	18.36
64.000	102	18.18
68.000	1	.18
71.000	1	.18
72.000	1	.18
73.000	25	4.46
75.000	70	12.48
76.000	24	4.28
77.000	12	2.14
78.000	35	6.24
80.000	1	.18
85.000	1	.18
89.000	11	1.96
92.000	2	.36
93.000	12	2.14
97.000	106	18.89